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## Greenhouse gas emission reductions from domestic anaerobic digesters linked with sustainable sanitation in rural China

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### Abstract

Anaerobic digesters provide clean, renewable energy (biogas) by converting organic waste to methane, and are a key part of China's comprehensive rural energy plan. Here, experimental and modeling results are used to quantify the net greenhouse gas (GHG) reduction from substituting a household anaerobic digester for traditional energy sources in Sichuan, China. Tunable diode laser absorption spectroscopy and radial plume mapping were used to estimate the mass flux of fugitive methane emissions from active digesters. Using household energy budgets, the net improvement in GHG emissions associated with biogas installation was estimated using global warming commitment (GWC) as a consolidated measure of the warming effects of GHG emissions from cooking. In all scenarios biogas households had lower GWC than non-biogas households, by as much as 54%. Even biogas households with methane leakage exhibited lower GWC than non-biogas households, by as much as 48%. Based only on the averted GHG emissions over 10 years, the monetary value of a biogas installation was conservatively estimated at US\$28.30 (\$16.07 ton<sup>-1</sup> CO<sub>2</sub>-eq.), which is available to partly offset construction costs. The interaction of biogas installation programs with policies supporting improved stoves, renewable harvesting of biomass, and energy interventions with substantial health co-benefits, are discussed.

### Keywords

biogas; anaerobic methanogenesis; sustainable sanitation; climate change; co-benefits; carbon offsets; global warming potential

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## Introduction

Improved access to clean fuels for cooking and heating, the most energy intensive activities among the world's poor, has been identified as crucial to attaining UN Millennium Development Goals [1]. In China, more than half the population is rural, most relying on traditional solid fuels, such as coal, wood, and crop residues for household cooking [2]. Indoor air pollution from burning these fuels is currently the largest environmental health risk factor in China, leading to an estimated 420,000 premature deaths per year [2]. Moreover, typical stoves poorly combust these fuels, emitting greenhouse gases (GHG) with broad public health consequences [3, 4]. In addressing rural energy needs, China has implemented one of the most successful improved stove dissemination programs in the world [5]. Yet while improved stoves have greater fuel efficiency, they have also been shown to have higher emissions of incomplete combustion products, with consequences for both public health and climate [6].

A move towards clean energy technologies for the rural population in China could reduce GHG emissions associated with non-renewable coal and incomplete combustion of solid fuels, while simultaneously easing the burden of disease associated with exposure to indoor air pollution [3]. A key technology which may permit a switch from solid fuels to cleaner gaseous fuels in rural China is anaerobic digestion, where organic human and animal wastes are digested under anaerobic conditions generating biogas, composed primarily of methane ( $\text{CH}_4$ ), which can be sequestered and burned for cooking, heating and lighting [7]. Through multiple programs, China is rapidly investing in biogas infrastructure, with a national target of 27 million systems installed in 2010, up from 9.8 million households in 2000 [8, 9]. Because these systems also provide basic sanitation services [7], their widespread installation has the potential to simultaneously achieve multiple energy and public health goals by improving rural sanitation and respiratory health while providing a low-cost, renewable rural energy supply and mitigating GHG emissions [7].

When fuel from biogas systems directly replaces non-renewable sources such as coal, there is a clear GHG benefit of their adoption [10]. Even replacing renewably harvested biomass fuels with biogas provides a significant GHG benefit due to reduction of incomplete combustion products such as  $\text{CH}_4$  and non-methane hydrocarbons [NMHC; 11]. Biogas is approximately 700,000 ppm  $\text{CH}_4$  [12], a potent GHG with a global warming potential (GWP) 25 and 72 times that of  $\text{CO}_2$  over a 100 year and 20 year time horizons, respectively [13]. Any gains made reducing GHG emissions by substituting biogas for solid fuels could be offset by  $\text{CH}_4$  leaked from biogas systems directly into the atmosphere. Previous studies in China have addressed social, economic and climate aspects of anaerobic digesters [14], but have not quantified the net change in GHG emissions, nor the operational inefficiencies, observed in actual use [15]. Here, global warming commitment (GWC), defined as the total atmospheric warming committed by an emission of a gas mixture emitted by fuel burning, is used to quantify the net change in GHG emissions associated with biogas systems. Annual GWCs of biogas and non-biogas households are quantitatively compared by combining field measurements of  $\text{CH}_4$  vented from biogas digesters with energy budgets for households with and without biogas systems.

## Methods

### Study area

About one fifth of China's biogas systems are installed in Sichuan Province [16], where the Ministry of Agriculture finances anaerobic digester construction through integrated improvement grants that fund simultaneous renovation of household kitchens, latrines and livestock sheds [7]. The systems are operated in a pressurized state that propels gas into the

household via plastic tubing. This positive pressure is maintained by wax, concrete and earthen seals which prevent biogas leakage and inhibit the intrusion of oxygen into the chamber. A typical 8 m<sup>3</sup> digester can generate 250–300 m<sup>3</sup> yr<sup>-1</sup> biogas in southern China, and 150–200 m<sup>3</sup> yr<sup>-1</sup> in the colder northern areas [17]. Typical systems in Sichuan are fixed-dome, 6–10 m<sup>3</sup> underground tanks with ground-level input and output ports and specific design and construction parameters described elsewhere [7]. This study surveyed six agricultural villages (SI Figure S1) located in the Chuanbei region of Sichuan Province, People's Republic of China (E104°29' N31°06'). The villages lie on the hilly, agricultural areas surrounding the city of Deyang (or 100 km NE of Chengdu, Sichuan's capital city), a region characterized by a subtropical climate suitable for efficient methanogenesis. About 19 percent of households have and use a biogas system in their home[14].

### Household surveya

A convenience sample of 67 heads of household representing a total of 326 household members in six villages in Jingyang and Zhongjiang counties were selected for a detailed questionnaire about their current and past energy usage; 32 of the households had a functioning biogas system, while the remainder used traditional fuel sources. Participants were asked to disclose their household demographics, fuel sources, energy consuming activities, and animal husbandry activities. Additionally, biogas households were questioned about the performance, maintenance and use of household biogas, and their digesters were surveyed for CH<sub>4</sub> leakage as described below. All surveys were independently, forward and back translated, and administered with free and informed participant consent by trained personnel from the Sichuan Centers for Disease Control and Prevention. Interactions with human participants were approved by the Institutional Review Boards of the University of California at Berkeley, Emory University and the Sichuan Centers for Disease Control, Chengdu, PRC, prior to data collection.

### Leak identification and quantification

In order to assess the prevalence and intensity of system failures, CH<sub>4</sub> leaks were characterized using a combination of path-integrated concentration measurements and radial plume mapping techniques. Thirty-two biogas systems present in surveyed households were scanned in July 2009 using a Remote Methane Leak Detector (RMLD; Health Consultants, Houston, TX) to discover fugitive CH<sub>4</sub> emissions in demarcated area above the underground digester. The scanning area included a zone at least 1 meter beyond the boundaries of the underground digester, as well as along seals and plastic tubing where seal failures or structural defects in the system may be found. A background CH<sub>4</sub> concentration was collected for each residence by taking a twenty second static reading with the RMLD pointed directly at the ground from a height of one meter and at a location at least 10 meters upwind from any known probable CH<sub>4</sub> source. The demarcated zone was then scanned with the RMLD by moving the laser in a sweeping zigzag pattern in 1 meter wide swathes according to the manufacturer's protocol. If a concentration above background was observed during the sweep, the scanning range and speed was reduced until a location of maximal concentration was established and marked with a survey flag for plume mapping. In addition to the ground surface above the tank, cap, dome perimeter, intake points and piping from the digester to point of use (e.g. household kitchen) were also scanned.

Gaseous flux from each identified leak was estimated following methods developed for plume mapping using multiple path-integrated concentration measurements [18]. Readings were taken across multiple vertical planes at, and downwind of, the area of interest and used to construct a concentration profile. With the RMLD mounted on a tripod, path-integrated concentration readings were taken at 25 target points arranged in a grid pattern perpendicular to the ground crossing through the area of a suspected leak (Figure 1).

Additionally, two sets of five readings were taken along a vertical target aligned with the grid but placed at points closer to the RMLD. The size of the grid varied for each site, but it typically was 2m long by 1m high with rows spaced by 25cm and columns, by 50cm. Best efforts were made to position the RMLD and target grid such that the suspected source was approximately at the midpoint between the two, with the prevailing wind perpendicular to the measurement path. Four RMLD measurements (~0.3 sec/measurement) were made at each target point, and two replicates of the entire procedure were carried out at each leak location. Wind speed, direction and temperature were recorded every three seconds using a HOBO Micro Station data logger (ONSET Computer Corporation, Bourne, MA, USA).

A Vertical Radial Plume Mapping (VRPM) approach [18–20] was used to reconstruct the concentration field in the vertical plane at each leak site. A smooth basis functions minimization (SBFM) algorithm [21] was used to fit the parameters of the bivariate Gaussian function to planar path-integrated concentration measurements as follows. From a given set of planar path-integrated concentration data, random selections of measurements (minimum 5) in the planes were drawn for fitting by SBFM to generate a set of 10,000 possible realizations of two-dimensional concentration fields. The concordance correlation factor (CCF), which compares measured path-integrated concentrations to those specified by identical paths taken through the reconstructed field, was used to assess the validity of each reconstruction [18]. Reconstructions with  $CCF < 0.6$  show poor fit to the Gaussian mathematical function, and were therefore discarded. Products of each accepted reconstructed field and associated perpendicular median wind speed at the site were calculated to obtain a range of flux estimates for each leak site. The median mass flux of all detected biogas leaks was input into the GWC model as described below.

### Household energy budget

Cooking energy budgets for households with and without biogas systems were developed based on the household survey in order to calculate household GHG emission rates. Cooking fuel usage was estimated for biogas, coal, firewood, straw, and liquefied petroleum gas (LPG) fuels. For households with biogas systems (BG households) and those without biogas systems (NB households), the contribution of each cooking fuel type to the energy delivered to cooking pot was estimated as follows. First, reported annual cooking fuel expenditures were converted into mass of fuel used per day based on current market values. Daily cooking fuel usage was converted into energy delivered to cooking pot, adjusting for efficiency of stove/fuel combinations, based on an existing emissions database and standard methods [11]. The proportional contribution of each fuel type to daily household cooking energy use was then used to estimate GHG emissions and the resulting GWC of BG and NB households.

### Greenhouse gas emissions and global warming commitment

Household emissions of GHG from cooking activities were estimated using a uniform daily budget (2 MJ) of energy delivered to the cooking pot of all households following standard methods [11, 22], roughly equivalent to the energy required for cooking two meals. GWCs are expressed per 2 MJ delivered to pot, and are calculated assuming that, while BG and NB households use the same quantity of energy delivered to pot, the efficiency and GHG emissions per unit of energy delivered to pot varies between BG and NB households based on the mixture of fuels used as informed by the household survey.

GWCs for wood burning stoves are calculated using ultimate emissions, which, unlike instant emissions, include unburned char and represent a more realistic combustion scenario where left over char is saved and subsequently burned alongside wood and converted to airborne carbon species at the next meal [11]. Based on previous work, GWC was estimated

for BG and NB households based on the relative GHG emissions from their fuel mix, where GWC for each stove is defined as [11]:

$$GWC = \sum GHG_i \times GWP_i$$

where  $GHG_i$  is moles of the  $i$ th GHG observed, and  $GWP_i$  is defined as the total warming per mole of the  $i$ th GHG compared to  $CO_2$  based on the most recent IPCC assessment [23, 24]. As the validity of single time horizon GWP estimates has been questioned [24], GWCs for 20, 100 and 500-year time horizons were estimated. The GHGs considered were  $CO_2$ , CO,  $CH_4$ ,  $NO_2$  and NMHC. Their GWPs for both renewable and non-renewable scenarios, described below, are listed in SI Table S1.

Four household models were explored in this study (Error! Reference source not found. Error! Reference source not found.1). Model 1 represents NB households. Three alternative BG household models were created: a simple BG model (Model 2), a model including  $CH_4$  leakage (Model 3), and a model accounting for modified biogas digester performance during cold months (Model 4). In Sichuan, anaerobic digesters generally produce biogas approximately 10 months out of the year, and thus a simple sinusoidal function based on seasonal temperature cycling in Sichuan was used in Model 4 to represent the decrease in biogas approaching December, transitioning back to full biogas use again in February. During cold periods with no or limited biogas production, modeled BG households were assumed to switch to the NB fuel mixture. The time-weighted average GHG emissions from the annual seasonal cycle was used to calculate GWC for Model 4. Daily biogas leakage estimated by radial plume mapping was added to the GHG emissions in Models 3 and 4 based on the gaseous composition of biogas [25], and in Model 4, leakage was also adjusted for temperature-sensitive, seasonal biogas production.

Six scenarios in this study stem from different GWC accounting methods associated with two renewable energy scenarios and three different stove distribution scenarios (Table 1). The GWCs of the four models were evaluated under each of the six GWC accounting scenarios for three time horizons. In renewable energy scenarios, biomass (wood, agriculture waste and animal dung) is assumed to be renewably harvested, meaning that  $CO_2$  emissions are completely returned to a vegetative sink yielding no net increase in GWC from  $CO_2$  [6, 23]. Completely efficient combustion of renewably harvested biomass fuels would result in zero GWC. However most stoves (including biogas and traditional stoves) generate products of incomplete combustion such as CO,  $CH_4$  and NMHC, which are eventually converted into  $CO_2$  in the atmosphere but have a significant impact on climate forcing before conversion. Thus, renewable energy scenarios account for renewably harvested fuels by adjusting the GWP of each gas emitted (subtracting 1.0 from the GWP for  $CO_2$ , CO,  $CH_4$ , and NMHC), resulting in a smaller net addition to GWC (SI Table S1). In contrast, non-renewable scenarios treat straw and biogas fuels as renewable and coal and firewood as non-renewable.

To address variation in the distribution of improved stoves among households, and the potential impact of an improved stove program, models were subjected to three alternative stove distributions: (1) improved stoves in all households, (2) no improved stoves in any household, and (3) all stove types uniformly distributed among households, for each respective fuel type [11]. Descriptions of stoves used in the models are shown in SI Table S2. Since limited data are available regarding the distribution of stove types used in China [26], in scenario variant 3, equal use of all stove models (both improved and non-improved) is assumed for each fuel type in the Chinese stove emissions database [11].



## Uncertainty and sensitivity analysis

Variation in stove upkeep, stove usage and other behavioral sources of uncertainty were not quantified in this analysis. However, substantial uncertainty in emissions factors reported in the Chinese stove emissions database [11] was propagated through the GWC estimation procedure to obtain a range of GWCs representing the influence of a single source of uncertainty associated with each particular fuel/stove combination. Application of emissions factors assumes that stoves are in an operable condition equivalent to the standardized conditions used to construct the stove emissions database. Scenario-based sensitivity analysis was conducted to investigate the influence of temperature, stove distribution and renewable harvesting on GWC of leaking biogas households (SI 1).

## RESULTS

### Household survey

The average annual income of all surveyed households was 14,220 RMB (range: 550 – 100,000 RMB; USD 1 = ~ 7 RMB), and no statistical difference was detected between BG and NB households ( $p=0.16$ ). More than 80% of respondents identified as farmers. All 32 BG households reported their digesters were constructed within the past 5 years (average age 2.4 years) following standard concrete and brick design with 10cm digester walls. The average reported cost of digester construction was approximately 1,900 RMB, with more than 90% of families having received government subsidies averaging about 400 RMB. Plastic piping was used in all BG households to channel gas to point of use. Wood and crop residues dominated solid cooking fuels in BG and NB households, with a small amount of coal use. Biogas was exclusively used for cooking and heating water. Daily cooking energy usage from solid fuels of NB households and BG households before biogas was installed are comparable (SI Table S3). In order to minimize modeled differences between BG and NB households, a conservative assumption was made that BG households used total cooking energy equal to that reported by NB households; therefore, the BG household deficit in energy usage (SI Table S3) was assumed to be biogas.

### Leak measurements and flux estimation

The mean background  $\text{CH}_4$  path-integrated concentration was 9.80 ppm-m ( $\text{SD}=11.8$ ; range 0–105;  $n=126$ ). Because households were well-ventilated, background measurements did not significantly differ between indoor and outdoor ( $p=0.63$ ). Small  $\text{CH}_4$  leaks were detected at 3 BG households, suggesting that most systems were well-maintained with minimal fugitive emissions. Where leakage was detected, consistent measurements at the source were typically 100200 ppm-m  $\text{CH}_4$  (SI Figure S2). A simulated leak from an intentionally opened system valve resulted in measurements on the order of  $1.0 \times 10^3$  ppm-m  $\text{CH}_4$  (data not shown). Figure 2 illustrates a reconstructed plume for one set of BG household measurements after background subtraction. Median  $\text{CH}_4$  mass flux estimated from the product of plume reconstructions with  $\text{CCF} > 0.6$  and associated perpendicular median wind speed at each leak site was  $0.067 \text{ g hr}^{-1}$  (mean absolute deviation: 0.97).

### Global warming commitment

In all scenarios, BG households showed reduced GWC as compared to NB households. Table 2 and SI Figure S4 give GWCs for households with and without biogas based on 20-yr, 100-yr and 500-yr GWPs. In NB households, modeled GWCs (as  $\text{g-CO}_2\text{-eq. per 2 MJ}$ ) range from 986 to 2350 over the 20 year horizon, from 359 to 1631 over the 100 year horizon and from 128 to 1308 over the 500 year horizon; uncertainty in GWC estimates associated with variation in emissions factors is shown for the 100 year horizon in SI Table S4. BG households show 23% to 55% reductions in GWC as compared with NB

households. Introducing leakage to a modeled BG household using renewable fuel sourcing adds 17% to 40% (temperature-sensitive and total leakage, respectively) to the GWC expected without leakage when evaluated over a 20 year horizon. For non-renewable scenarios, leakage adds 34% to 73% (temperature-sensitive and total) to the GWC expected without leakage over the same horizon (SI 1). Thus, about a sixth to three fourths of GHG benefits of biogas can be negated by a poorly maintained system under short time-horizons. Compared to leakage and renewable fuel sourcing, stove distribution had a more modest effect on the reduction in GWC in BG households (SI 1 and Table S5), yet stove distribution had a large impact on NB households as would be expected (Table 2).

## DISCUSSION

Using both field measurements of CH<sub>4</sub> leakage from anaerobic digesters and household energy budgets, the GWC of BG and NB households were modeled under several GHG accounting scenarios, accounting for temperature dependence of digester performance, varying distribution of stoves and renewable sources of energy. Because of the relatively high GWP of CH<sub>4</sub>, any GHG emission reductions made by replacing traditional cooking fuels with biogas digesters could easily be negated by a moderate CH<sub>4</sub> leak. Determining the prevalence and intensity of CH<sub>4</sub> leaks from biogas digester systems clarified the extent to which biogas interventions offer GHG benefits. In our study, all scenarios in which NB were compared to BG households, including scenarios taking into account system leakage, BG households had lower GWC than their NB counterparts. Moreover, models incorporating leaks (Models 3 and 4) made the highly conservative assumption that all BG systems leak, whereas only ~10 percent of surveyed systems showed detectable leaks.

Based only on the benefits of reduced GHG emissions, the monetary value of a biogas installation can be estimated on the current carbon market. Observed reductions in GWC among BG households range from 24.5 to 5.1 mol-CO<sub>2</sub> equivalents per 2 MJ. To calculate the value of averted emissions to a household replacing 2 MJ of cooking fuel per day with biogas over 10 years, the Certified Emissions Reduction rate as of June 2010 of \$16.07 per ton of offset CO<sub>2</sub>-eq and a discount rate of 3% were used [27, 28]. Based on the modeled change in emissions observed in Sichuan province, averted carbon over 10 years of household use was conservatively valued at \$28.30, which, in addition to the savings associated with averted fuel use, can contribute to digester's construction cost.

Among stoves sharing the same fuel type, there is a wide variation in GWC depending on stove technology (SI Figure S4; [11]). For instance, among stoves that use coal there is a nine-fold difference between the lowest and highest GWC. Interestingly, GWC of the biogas stove is one sixth of the GWC of the lowest emitting traditional fuel source, the straw burning stove, and half the GWC of coal burning stoves. Thus data describing the specific distribution of stoves in the population would raise confidence in the GWC estimated for a particular community subset.

Using an ultimate emission assumption, improved wood stoves had lower GWC than non-improved stoves. If only instant emissions are considered, however, improved wood-burning stoves may have a larger GWC contribution because of variation in combustion efficiencies associated with using char as a fuel source. Improved stoves have greater heat transfer efficiency at the cost of reduced combustion efficiency [11]. Reduced combustion efficiency led to greater emissions of products of incomplete combustion (e.g. NO<sub>2</sub>, CO, NMHC, CH<sub>4</sub>), which in turn lead to higher GWC of improved stoves using an assumption of instant emissions [11]. Products of incomplete combustion accounted for the increase in GWC seen in the 100% improved stove distribution scenarios as compared to the 0% improved stove scenarios.

The GWC reductions in BG households examined in this study were more sensitive to renewable harvesting than stove distribution or temperature-sensitive leakage (SI 1 and Table S5). The greatest proportional increases in GWC from leakage are observed in renewable energy models, which, because they have fewer GHG emissions overall, result in leakage assuming a greater proportion of GWC. As expected, the increase in GWC associated with CH<sub>4</sub> leakage is reduced when the effect of temperature on CH<sub>4</sub> production is accounted for.

Differences between renewable and non-renewable models in Table 2 result from CO<sub>2</sub> being recycled back into the environment. The choice between renewable/non-renewable biomass harvesting showed a greater impact on a household's GWC than the choice between biogas/non-biogas. It should be noted, however, that the effect of renewable harvesting was accentuated by defining the scenario as 100 percent renewable biomass sourcing, a very ambitious target. GWC of uniform stove distributions for the 20-yr model was 80% higher in the non-renewable energy model as compared to renewable energy model. This was due to large contributions of CO<sub>2</sub> from wood burning stoves, and highlights the significant impact that renewable harvesting can have on limiting carbon emissions from household energy use. In order to assess the validity of the renewable energy model, data on the fraction of fuels being nonrenewably harvested in the area are needed, including information on regional woodfuel resources, harvesting practices and use [29, 30]. In the absence of these data, our models represent the range of outcomes associated with conservative (minimal renewable harvesting) and optimistic (extensive renewable harvesting) assumptions.

This analysis assumed that BG and NB households consume the same quantity of energy delivered to each pot. This assumption may inflate BG household GWC by overestimating the amount of biogas required to accomplish the same tasks in a NB household. Deriving biogas energy from waste material may free up capital to increase and/or diversify energy purchases. With respect to cooking, however, the data suggested that cooking activities of NB households and BG households before biogas adoption consume approximately the same amount of energy to pot. Furthermore, total energy usage in biogas households might decrease because biogas gives highly resolved control over energy use in ways solid fuel combustion does not. Biogas stoves can be turned on and off quickly and easily, whereas solid fuel fires smolder and are difficult to restart after extinguishing and thus households may keep solid fuel fires burning throughout more of the day.

This limited investigation of uncertainty resulting from variance of emission factors for each of these scenarios was generally larger for NB households than for BG households (SI Table S4) as a result of the particular variety of fuels and stoves used by NB households. Compared to other populations in Sichuan, the region studied here relied more on wood and crop residues for cooking fuel, and less on coal [7, 31]. Similar analyses conducted in a coal-dependent community would likely reveal a greater carbon benefit and, accordingly, a greater value to the global carbon market than shown here.

## Conclusion

Biogas digesters provide a renewable source of energy that reduces household GWC compared to NB households, even when accounting for system failures. In the face of major environmental challenges facing rural China, and the increasing importance of mitigating global climate change, policies that integrate rural energy needs, public health goals and GHG emissions reduction are increasingly urgent [2]. Thus policy incentives to establish anaerobic digesters, as well as other energy interventions with substantial health co-benefits (e.g. improved stoves), along with renewable harvesting policies, are essential.



## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

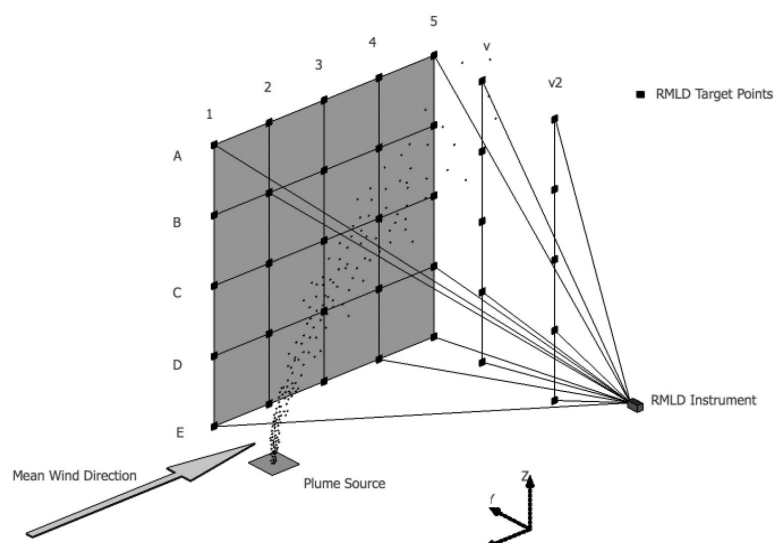
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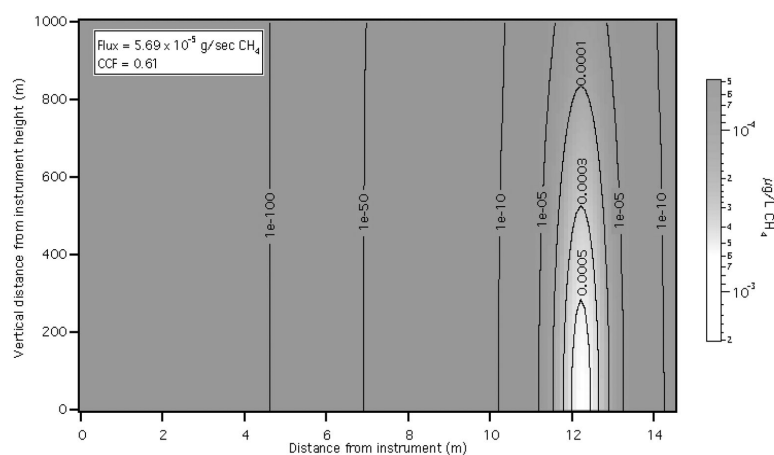
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**Figure 1.** Experimental setup for plume mapping using multiple path-integrated concentration measurements taken along paths targeting 35 grid points. Only selected paths for path-integrated concentration measurements are shown for clarity.



**Figure 2.** Methane concentration profile reconstructed using radial plume mapping of one set of ppm-m measurements collected at a leaking biogas location in Gaohuai village.

**Table 1**

GWC models for households with and without biogas systems, renewable energy and stove scenarios, and time horizons explored in this analysis.

<b>Model 1:</b> Households without biogas digesters	<b>Scenario 1:</b> Renewable biomass energy sourcing and 100% improved stove distribution	
<b>Model 2:</b> Households with biogas digesters without biogas leakage	<b>Scenario 2:</b> Renewable biomass energy sourcing and uniform stove distribution <b>Scenario 3:</b> Renewable biomass energy sourcing and 0% improved stove distribution	<b>Horizon 1:</b> 20 years <b>Horizon 2:</b> 100 years <b>Horizon 3:</b> 500 years
<b>Model 3:</b> Households with biogas digesters including biogas leakage	<b>Scenario 4:</b> Non-renewable biomass energy sourcing and 100% improved stove distribution	
<b>Model 4:</b> Households with biogas digesters including biogas leakage adjusted for temperature sensitive production	<b>Scenario 5:</b> Non-renewable biomass energy sourcing and uniform stove distribution <b>Scenario 6:</b> Non-renewable biomass energy sourcing and 0% improved stove distribution	



**Table 2**

GWC as g-CO<sub>2</sub> per 2 MJ for all modeled households over 20, 100 and 500 year time horizons. Percent reduction in GWC (compared to households without biogas digesters) is shown in parentheses for households with digesters using alternative stove distributions, renewable and non-renewable fuel sourcing, and accounting for leakage.

20-year Time Horizon					
Stove distribution	Harvesting model	Household GWC (% reduction in GWC)			
		Non-biogas <sup>†</sup>	Biogas total <sup>I</sup>	Biogas TSL <sup>2</sup>	Biogas without leak
0% improved	Non-renewable	2350	1483 (37%)	1366 (42%)	1164 (50%)
	Renewable	1239	919 (26%)	801 (35%)	599 (52%)
Uniform	Non-renewable	2089	1329 (36%)	1212 (42%)	1010 (52%)
	Renewable	1155	855 (26%)	738 (36%)	536 (54%)
100% improved	Non-renewable	1702	1125 (34%)	1007 (41%)	805 (53%)
	Renewable	986	761 (23%)	644 (35%)	441 (55%)

100-year Time Horizon					
Stove distribution	Harvesting model	Household GWC (% reduction in GWC)			
		Non-biogas <sup>†</sup>	Biogas total <sup>I</sup>	Biogas TSL <sup>2</sup>	Biogas without leak
0% improved	Non-renewable	1631	921 (44%)	881 (46%)	810 (50%)
	Renewable	520	357 (31%)	316 (39%)	246 (53%)
Uniform	Non-renewable	1388	796 (43%)	755 (46%)	685 (51%)
	Renewable	454	322 (29%)	281 (38%)	211 (54%)
100% improved	Non-renewable	1075	638 (41%)	598 (44%)	527 (51%)
	Renewable	359	275 (23%)	234 (35%)	164 (54%)

500-year Time Horizon					
Stove distribution	Harvesting model	Household GWC (% reduction in GWC)			
		Non-biogas <sup>†</sup>	Biogas total <sup>I</sup>	Biogas TSL <sup>2</sup>	Biogas without leak
0% improved	Non-renewable	1308	690 (47%)	677 (48%)	656 (50%)
	Renewable	197	125 (37%)	113 (43%)	91 (54%)
Uniform	Non-renewable	1100	585 (47%)	573 (48%)	551 (50%)
	Renewable	167	111 (34%)	98 (41%)	77 (54%)
100% improved	Non-renewable	844	456 (46%)	444 (47%)	422 (50%)
	Renewable	128	92 (28%)	80 (38%)	59 (54%)

<sup>†</sup>Reference group for % reduction in GWC

<sup>I</sup>Biogas total: GWC from biogas households including non-adjusted CH<sub>4</sub> leakage data;

<sup>2</sup>Biogas TSL (temperature-sensitive leak): GWC from biogas households including CH<sub>4</sub> leakage adjusted for seasonal ambient temperature change.